LASERS | Microchip Lasers*

John J. Zayhowski
Lincoln Laboratory, Massachusetts Institute of Technology
244 Wood Street, Lexington, MA 02420-9108 USA
E-mail: zayhowski@ll.mit.edu

Abstract

Microchip lasers are a rich family of solid-state lasers defined by their small size, robust integration, reliability, and potential for low-cost mass production. Continuous-wave microchip lasers cover a wide range of wavelengths, often operate single frequency in a near-ideal mode, and can provide a modest amount of tunability. *Q*-switched microchip lasers provide the shortest output pulses of any *Q*-switched solid-state laser, with peak powers up to several hundred kilowatts. This article discusses the various types of microchip lasers, the physics that underlies their performance, typical operating parameters for the devices, and several of their applications.

Keywords
Composite-cavity laser, Diode-pumped laser, Laser, Microchip laser, Miniature laser, Monolithic laser, Passively *Q*-switched laser, *Q*-switched laser, Saturable absorber, SESAM, Solid-state laser

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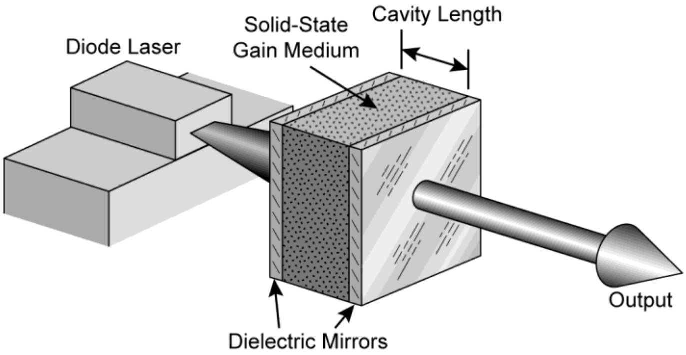


Figure 1.
Illustration of a monolithic microchip laser.

Introduction

Microchip lasers are a rich family of solid-state lasers defined by their small size, robust integration, reliability, and potential for low-cost mass production. In its simplest embodiment, a microchip laser is a monolithic device that consists of a small piece of solid-state gain medium polished flat and parallel on two opposing sides. Dielectric cavity mirrors are deposited directly on the gain medium and the laser is pumped with a diode laser, either directly, as shown in Fig. 1, or via an optical fiber. In other embodiments, two or more materials are joined together before being polished and dielectrically coated to form a composite-cavity microchip laser with added functionality or enhanced mode properties. For example, the additional material could be an electro-optic material to enable frequency tuning of the laser, a nonlinear material for intracavity wavelength conversion, a saturable absorber to *Q* switch the device, or a passive transparent material to increase both the transverse mode area and the output power of the laser.

Continuous-wave (cw) microchip lasers cover a wide range of wavelengths, often operate single frequency in a near-ideal mode, and can provide a modest amount of tunability. *Q*-switched microchip lasers provide the shortest output pulses of any *Q*-switched solid-state laser, with peak powers up to several hundred kilowatts. The average output power of microchip lasers is typically in the range from several tens to several hundreds of milliwatts.

Background

Most solid-state lasers are built from discrete optical components that must be carefully assembled and critically aligned. Laser assembly is typically performed

by trained technicians, and is time consuming and expensive. As a result, the cost of most solid-state lasers makes them unattractive for a wide range of applications for which they would otherwise be well suited. Additional characteristics that have historically impeded the widespread use of solid-state lasers include their size and reputation for being fragile and unreliable. This was even truer in the early 1980s, the infancy of microchip laser development, than it is today. Microchip lasers were developed to overcome these limitations—cost, size, robustness, and reliability—and thereby become viable components for a variety of large-volume applications. The term ‘microchip laser’ was coined at MIT Lincoln Laboratory in the early 1980s to draw an analogy between this new class of lasers and semiconductor electronic microchips with their inherent small size, reliability, and low-cost mass production.

Consider the simplest of all possible microchip lasers, a small piece of solid-state gain medium polished flat and parallel on two opposing sides, with dielectric cavity mirrors deposited directly onto the polished faces, as shown in Fig. 1. Fabrication of the laser starts with a large boule of gain material, such as Nd:YAG. The boule is sliced into wafers about 0.5 mm thick. The wafers are then polished and dielectrically coated before they are diced into 1-mm-square pieces, with each piece being a complete laser. One boule can produce thousands of lasers, and throughout the fabrication process the lasers never need to be handled independently.

To complete a microchip laser system, the laser must be coupled to a pump source. Microchip lasers are pumped with semiconductor diode lasers. The 1980s were a time of rapid development in diode lasers. The amount of power that was available from commercial diode lasers was rapidly increasing and the cost per watt of output power was quickly decreasing, with projections of extremely inexpensive, high-power diode lasers in the near future. As a result, diode lasers fit nicely into the picture of low-cost microchip laser systems. To keep the cost of the system low, it is important that the coupling of the diode to the microchip laser be performed inexpensively. The use of a flat-flat laser cavity eliminates any critical alignment between the diode and the laser and makes the assembly of the system quick and simple, with the potential for inexpensive automation.

The use of simple, small, monolithic, mass-produced solid-state lasers noncritically coupled to low-cost semiconductor diode pump lasers gives microchip laser systems their defining characteristics—small size, robust integration of components, reliability, and the potential for low-cost mass production—and differentiates them from other miniature laser systems that are designed and constructed using more conventional techniques.

Since their early development, microchip lasers have evolved into a rich family of devices with capabilities that often exceed those of conventional lasers. The first microchip lasers developed operated cw, and a variety of cw microchip lasers were quickly demonstrated, covering a wide range of wavelengths. Some of the early applications required a modest amount of tunability, and several tuning mechanisms were incorporated into the laser structure. It was not long before researchers realized that the short cavity lengths inherent to microchip lasers gave them tremendous potential as pulsed devices. This led to the development of actively *Q*-switched microchip lasers, quickly followed by the most successful variation of microchip laser, the passively *Q*-switched microchip laser, which has demonstrated the shortest output pulse of any *Q*-switched solid-state laser.

Overview

Monolithic Microchip Lasers

The earliest microchip lasers were monolithic devices based on optical transitions in the Nd^{3+} ion near 0.94, 1.06, or 1.32 µm, using a variety of gain media including Nd:YAG, NPP, LNP, Nd:GSGG, Nd:YVO_4, Nd:$LaMgAl_{11}O_{19}$, Nd:YCeAG, Nd:YLF, $Nd_xY_{1-x}Al_3(BO_3)_4$, Nd:La_2O_2S, Nd:MgO:$LiNbO_3$, and Cr,Nd:YAG. It was not long, however, before other active ions were investigated and monolithic microchip lasers were constructed at a wide variety of wavelengths. These include Cr:LiSAF microchip lasers operating in the 0.8- to 1.0-µm spectral region, Yb:YAG microchip lasers at 1.03 µm, Yb,Er:glass microchip lasers at 1.5 µm, Tm and Ho microchip lasers operating near 2 µm, Cr-doped chalcogenides microchip lasers near 2.3 and 2.5 µm, and Er-doped microchip lasers at 3 µm. Of the gain media demonstrated in microchip lasers, Nd:YAG and Nd:YVO_4 are the most commonly used.

All of the lasers listed above operate in a near-ideal fundamental transverse mode, and several operate single frequency (in a single longitudinal mode) with a narrow linewidth. The $Nd_xY_{1-x}Al_3(BO_3)_4$ microchip laser has another very interesting characteristic. In addition to being a good gain medium, $Nd_xY_{1-x}Al_3(BO_3)_4$ has a second-order nonlinearity that allows it to perform harmonic generation, and the microchip laser is self frequency doubled to produce green output at 531 nm. The Nd:MgO:$LiNbO_3$ microchip laser is electro-optically tunable. The doubly doped Cr,Nd:YAG laser is the only one of the lasers listed above that is not cw—it is self passively *Q* switched.

Composite-Cavity Microchip Lasers

The search for multifunctional gain media—gain media that simultaneously act as harmonic converters, electro-optical material, or passive *Q* switches—has led to several interesting monolithic devices. However, the multifunctional media are often less than ideal in one or more of their functions, and/or are difficult or expensive to grow. Higher-performance devices can be obtained by combining two or more specialized materials within the same composite cavity. In composite-cavity microchip lasers the constituent materials are bonded together to form a quasi-monolithic device, with dielectric mirrors deposited (or bonded) on the outer surfaces.

Several issues must be addressed in the design of composite-cavity microchip lasers. Different materials have different refractive indices and different thermal-expansion coefficients. The optical, mechanical, and thermal properties of the material interface must be dealt with in a way that satisfies the optical requirements of the laser cavity, is robust enough for the intended application, and is cost effective. Otherwise, the less-than-ideal performance of a monolithic device, if one can be constructed, may be the best solution.

Composite cavities have been successfully employed in coupled-cavity microchip lasers to obtain single-frequency operation from gain media with extremely broad gain bandwidths, harmonically converted green and blue cw microchip lasers, electro-optically tunable microchip lasers, actively *Q*-switched microchip lasers, passively *Q*-switched microchip lasers, and frequency-converted passively *Q*-switched microchip lasers.

Pumping

Microchip lasers are typically pumped by semiconductor diode lasers. The simplest configuration places the microchip laser in close proximity to the output facet of the pump diode with no intervening optics. As the amount of pump power increases, the diameter of the oscillating mode in a microchip laser usually decreases and, for this proximity-coupled configuration, the typically large divergence of the diode output overfills the oscillating mode volume resulting in inefficient operation or multi-transverse-mode oscillation. The situation can be improved by putting a lens between the diode and the microchip cavity, which is common practice in moderate- or high-power microchip laser systems (output powers in excess of several tens of milliwatts).

An alternative configuration for pumping microchip lasers uses fiber-coupled diode lasers. This configuration decouples the diode-laser system from the microchip cavity and offers several practical advantages. It separates the

engineering of the pump subsystem from the microchip cavity; it makes it easy to independently control the temperature of the diodes and the microchip cavity; and it facilitates an extremely compact laser head that can fit into small spaces, coupled to the rest of the system by a single, flexible optical fiber. High-power microchip lasers are often pumped by diode-laser arrays. In this case, fiber coupling serves the additional function of shaping the combined diode-laser output.

Transverse Mode Definition

Most microchip lasers use a flat-flat cavity design. The eigenmodes of a flat-flat cavity are plane waves, yet microchip lasers typically operate in a near-ideal, fundamental transverse mode with a well-defined mode radius. The mode-defining mechanisms vary depending on the gain medium, other media within a composite-cavity device, and pump power.

For many microchip lasers the transverse mode is determined primarily by thermal effects. When a microchip laser is longitudinally pumped, the pump beam deposits heat. In materials with a positive change in refractive index with temperature, such as Nd:YAG, this creates a thermal lens that stabilizes the cavity and defines the transverse mode. When the cavity mirrors are deposited directly on the gain medium the heat also induces curvature of the mirrors. For materials with a positive thermal-expansion coefficient this contributes to the stabilization of the transverse mode.

In three-level or quasi-three-level lasers there can be significant absorption of the oscillating light in unpumped regions of the gain medium. This creates a radially dependent loss that can restrict the transverse dimensions of the lasing mode. The mere absence of gain in the unpumped regions of the gain medium can have a similar effect. In passively *Q*-switched devices bleaching of the saturable absorber results in a dynamic aperture that opens as the *Q*-switched pulse forms and is an important mode-defining mechanism.

Optical gain provides dispersion. Gain-related index guiding has been shown to play an important role in Nd:YVO_4 microchip lasers, and can lead to interesting effects such as self *Q* switching.

Parallelism between the cavity mirrors can be critical for the creation of a circularly symmetric fundamental transverse mode in a flat-flat cavity. At high pump powers the mode-defining mechanisms in microchip lasers are usually thermal, and the requirement on parallelism is relaxed as the power of the

laser increases. The requirement is less severe in microchip lasers based on three-level gain media or employing a saturable absorber.

Methods consistent with low-cost mass fabrication have been developed to put curved mirrors on microchip lasers. Curved mirrors can stabilize the transverse mode of the laser when the mechanisms discussed above are not strong enough to do so. They can reduce the threshold of cw microchip lasers and make low-power operation more consistent from device to device. For a large variety of gain media they are not needed, especially when the laser is pumped with medium- or high-power diodes (typically more than several tens of milliwatts).

Typical mode radii of microchip lasers fall in the range from 20 to 150 μm, depending on the gain medium, pump power, cavity length, and several other factors. To ensure oscillation in the fundamental transverse mode, that mode must use most of the gain available to the laser. If the radius of the fundamental mode is much smaller than the radius of the pumped region of the gain medium, higher-order transverse modes will oscillate.

Spectral Properties

Single-Frequency Operation

As the cavity length of a laser decreases, its free spectral range increases. The original microchip-laser concept included making the laser cavity sufficiently short that its free spectral range is comparable to the gain bandwidth of the gain medium. Robust single-frequency operation can then be obtained as long as one of the cavity modes falls near the peak of the gain profile. This requires precise, subwavelength control of the cavity's optical length (length times refractive index), and is often accomplished through thermal control of the cavity.

Typically, each pulse of a *Q*-switched microchip laser is single frequency. However, at high repetition rates (when the interpulse timing is short compared to the relaxation time of the gain medium) consecutive pulses may correspond to different longitudinal modes.

Fundamental Linewidth

One contribution to the spectral width of all lasers is the coupling of spontaneous emission to the oscillating mode. This gives rise to the Schawlow-Townes linewidth, which has a Lorentzian power spectrum with a width that scales inversely with the output power of the laser. In microchip

lasers, thermal fluctuations of the cavity length at a constant temperature can result in a much larger fundamental linewidth. These fluctuations result in a Gaussian power spectrum that, for monolithic devices, scales as the inverse square root of the oscillating mode volume. Monolithic cw Nd:YAG microchip lasers with a cavity length of ~1 mm have a Gaussian spectral profile with a linewidth of several kilohertz, with spectral tails corresponding to a Lorentzian contribution of only a few hertz.

Single-frequency *Q*-switched microchip lasers have a Fourier-transform-limited optical spectrum that is much broader than the fundamental linewidth of cw devices.

Frequency Tuning

Microchip lasers are frequency tuned by changing the cavity’s optical length. The optical length can be changed using a variety of techniques including thermal tuning, stress tuning, and electro-optic tuning. Pump-power modulation represents a special case of thermal tuning. Each of these techniques allows continuous frequency modulation of a single longitudinal cavity mode.

Changing the temperature of an element in a laser cavity, or the entire cavity, is often the simplest way to tune a laser. A change in temperature results in a change to both the physical length of the component and its refractive index.

The cavity modes of a resonator also tune as elements within the cavity are squeezed. Squeezing transverse to the resonator’s optical axis results in an elongation of the material along the axis. Superimposed on this is the stress-optic effect. In crystals with cubic symmetry, the stress-optic effect can split the frequency degeneracy of orthogonally polarized optical modes. For squeezing along the optical axis of the cavity there is a compression of the squeezed elements and the frequency degeneracy of orthogonally polarized modes remains unchanged. By using a piezoelectric transducer to squeeze a monolithic Nd:YAG microchip laser, researchers demonstrated tuning at modulation frequencies up to 20 MHz, although nonresonant response was limited to ~80 kHz. The nonresonant tuning response was 300 kHz V^{-1}.

Many applications require high rates of frequency tuning that can only be achieved electro-optically. For high-sensitivity tuning it is desirable to fill the cavity with as large a fraction of electro-optic material as possible. However, it is often still important to keep the total cavity length as short as possible, to ensure single-frequency operation, to maximize the tuning range, and to minimize the response time. Composite-cavity electro-optically tuned

Nd:YAG/$LiNbO_3$ microchip lasers have been continuously tuned over a 30-GHz range with a tuning sensitivity of ~14 MHz V^{-1}. The tuning response was relatively flat for tuning rates from dc to 1.3 GHz. Monolithic Nd:MgO:$LiNbO_3$ and Nd:$LiNbO_3$ electro-optically tuned microchip lasers have also been demonstrated.

Changes in pump power induce frequency changes in the output of solid-state lasers. As the pump power increases more heat is deposited in the gain medium, causing the temperature to rise and changing both the refractive index and length. Because frequency tuning via pump-power modulation relies on thermal effects, it is often thought to be too slow for many applications. In addition, modulating the pump power has the undesirable effect of changing the amplitude of the laser output. However, for microchip lasers significant frequency modulation can be obtained at relatively high modulation rates with little associated amplitude modulation. For example, pump-power modulation of a 1.32-μm microchip laser has been used to obtain 10-MHz frequency modulation at a 1-kHz rate and 1-MHz frequency modulation at a 10-kHz rate, with an associated amplitude modulation of less than 5%. This technique has been employed to phase lock two microchip lasers and introduced less than 0.1% amplitude modulation on the slave laser. When it can be used, pump-power modulation has advantages over other frequency-modulation techniques since it requires very little power, no high-voltage electronics, no special mechanical fixturing, and no additional intracavity elements.

Polarization Control

Linear polarization is easily achieved in microchip lasers that employ an anisotropic gain medium, but can be problematic for monolithic microchip lasers with isotropic gain media. For lasers with isotropic gain media, the polarization degeneracy of the gain medium can often be removed by applying uniaxial transverse stress or asymmetric heat sinking. In the absence of any other polarizing mechanism, the polarization of the pump light, or asymmetry in its transverse mode profile, may determine the polarization of the laser output. In either of these cases, the polarization selectivity can be weak and the polarization of the laser may be sensitive to perturbations including external feedback.

In passively *Q*-switched microchip lasers that employ an isotropic gain medium it is often the properties of the saturable absorber that determine the polarization of the laser.

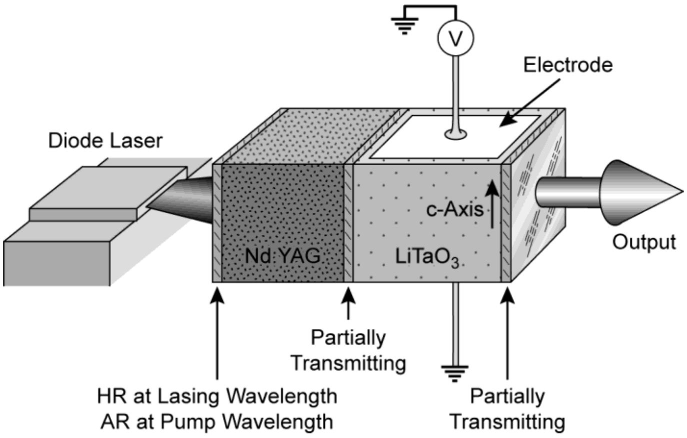


Figure 2.
Coupled-cavity electro-optically *Q*-switched microchip laser. HR = highly reflective, AR = antireflective

Pulsed Operation

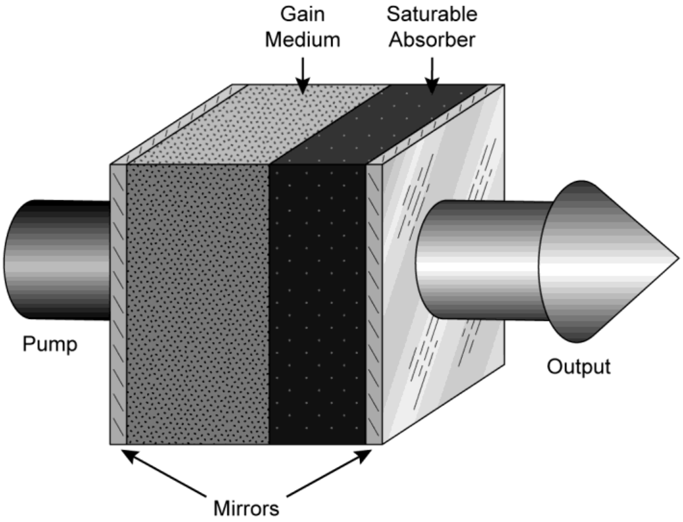
Pulsed output has been obtained from microchip lasers using a variety of techniques, including active *Q* switching, passive *Q* switching, and mode locking.

The shortest output pulse that can be obtained from a *Q*-switched laser has a full-width at half maximum of 8.1 times the round-trip time of light in the laser cavity divided by the natural logarithm of the round-trip gain. Since microchip lasers are physically very short, they have very short round-trip times. This leads to the possibility of producing very short *Q*-switched output pulses.

Active *Q* Switching

Actively *Q*-switched microchip lasers can be realized using the coupled-cavity configuration illustrated in Fig. 2. An etalon containing an electro-optic element ($LiTaO_3$) serves as a variable-reflectivity output coupler for a gain cavity defined by the two reflective surfaces adjacent to the gain medium (Nd:YAG). The reflectivity of the etalon for the potential lasing frequencies of the device is controlled by a voltage applied to a pair of electrodes in contact with the electro-optic material.

Coupled-cavity electro-optically *Q*-switched microchip lasers have demonstrated the shortest *Q*-switched pulses obtained from any actively *Q*-switched solid-state laser to date. A coupled-cavity Nd:YAG device, pumped with a 500-mW diode laser, produced 270-ps pulses with a pulse energy of 6.8 µJ at a repetition rate of 5 kHz. A coupled-cavity Nd:YVO_4 microchip laser pumped at



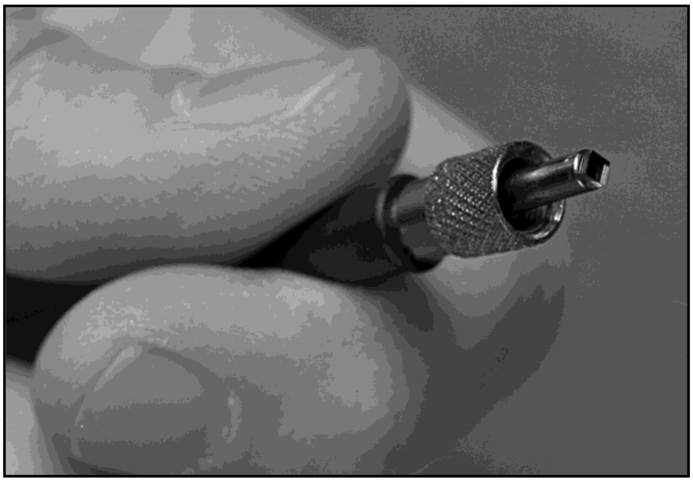


Figure 3.
Composite-cavity Nd:YAG/Cr^{4+}:YAG passively *Q*-switched microchip laser:
(top) schematic and (bottom) photograph of laser bonded to ferrule of pump fiber.

the same power level produced 115-ps pulses with a pulse energy of 12 μJ at a 1-kHz repetition rate. Pumped slightly harder, with a pump power of 1.2 W, a Nd:YVO_4 microchip laser demonstrated 8.8-ns pulses at pulse repetition rates as high as 2.25 MHz.

Passive *Q* Switching

Passively *Q*-switched microchip lasers contain a gain medium and a saturable absorber, as shown in the top of Fig. 3. When the gain medium absorbs sufficient pump energy that the gain in the laser cavity is greater than the loss, an intracavity optical field forms. The optical field saturates the loss of the saturable absorber and the gain of the gain medium. When the materials are chosen properly, the loss of the saturable absorber saturates more quickly

than the gain of the gain medium and the laser will *Q* switch, generating a short, intense pulse of light without the need for high-voltage or high-speed electronics.

In addition to simplicity of implementation, the advantages of a passively *Q*-switched laser include the generation of pulses with a well-defined energy and duration. The pulse energy and duration are determined by the design of the laser cavity and the material properties of the gain medium and passive Q switch. Passively *Q*-switched microchip lasers have demonstrated pulse energies and pulse widths with stabilities of better than 1 part in 10^4. This is achieved at the expense of pulse-to-pulse timing jitter, caused primarily by fluctuations in the pump source.

To manage thermal effects, high-power passively *Q*-switched microchip lasers are often pulse pumped. A common implementation uses an external clock to turn the pump diodes on and a signal generated by the *Q*-switched output pulse to turn them off. By using high-power pump diodes at a low duty cycle, larger amounts of energy can be stored in the gain medium of the laser with reduced thermal loading. This results in a larger oscillating mode diameter and more energetic pulses.

Q Switching with Bulk Saturable Absorbers

The most commonly used bulk saturable absorber for passive *Q* switching of microchip lasers is Cr^{4+}:YAG. It has been used to *Q* switch Nd:YAG microchip lasers operating at 946 nm, 1.064 μm, and 1.074 μm; Nd:YVO_4 microchip lasers operating at 1.064 μm; Nd:$GdVO_4$ microchip lasers operating at 1.062 μm; and Yb:YAG microchip lasers operating at 1.03 μm.

The combination of Cr^{4+}:YAG and a doped YAG gain medium, such as Nd:YAG, is particularly attractive from the point of view of an extremely robust device. Since both materials use the same host crystal, YAG, they can be diffusion bonded to each other in a way that blurs the distinction between a monolithic and a composite-cavity device. Both materials have the same thermal and mechanical properties and the same refractive index, and the bond between them can be sufficiently strong that the composite device acts in all ways as if it were a single crystal. An early, low-power, diffusion-bonded Nd:YAG/Cr^{4+}:YAG microchip laser is shown in the bottom of Fig. 3.

As an alternative to diffusion bonding, Nd:YAG can be epitaxially grown on Cr^{4+}:YAG and vice versa, using nonequilibrium growth techniques that can produce Nd or Cr^{4+} concentrations that could not otherwise be achieved. Cr^{4+},Nd:YAG can also be grown as a single crystal, although this approach

precludes some of the device optimization that can be achieved when the two materials are physically distinct.

Typically, $Nd:YAG/Cr^{4+}:YAG$ passively *Q*-switched microchip lasers are operated with an output coupling approximately equal to the single-pass loss of the unsaturated saturable absorber. The minimum pulse width that can be obtained is limited by the average inversion density that can be achieved within the oscillating mode volume, pump-induced bleaching of the saturable absorber, and a reduction in the gain cross section caused by heating of the gain medium as the laser is pumped harder. Passively *Q*-switched $Nd:YAG/Cr^{4+}:YAG$ microchip lasers typically produce pulses with full-widths at half maximum between 300 ps and ~1 ns, and pulses as short as 150 ps have been demonstrated.

The maximum pulse energy that can be obtained from passively *Q*-switched $Nd:YAG/Cr^{4+}:YAG$ microchip lasers is limiting the amount of stored energy the fundamental mode can access, and is strongly influenced by thermal effects. Devices pumped with a 1-W diode laser can generate 1.064-μm pulses with energies up to ~15 μJ and peak powers up to ~30 kW, at pulse repetition rates of ~10 kHz. Less energetic pulses, with lower peak powers, have been demonstrated at repetition rates up to 110 kHz. By pulse pumping microchip lasers with high-power diode-laser arrays, pulse energies up to ~30 μJ with peak powers up to ~100 kW are achieved at repetition rates of ~10 kHz; pulse energies of ~250 μJ with peak powers up to ~500 kW are obtained at repetition rates of ~1 kHz; and pulse energies of several millijoules with peak powers of several megawatts are achieved at repetition rates up to ~100 Hz.

The combination of Yb:YAG and $Cr^{4+}:YAG$ has the same potential as Nd:YAG and $Cr^{4+}:YAG$ for quasimonolithic and monolithic integration. The longer upper-state lifetime of Yb:YAG is attractive for low-repetition-rate systems since it allows the gain medium to accumulate energy for a longer time, making it possible to use lower-power, less-expensive pump diodes.

To date, the best results in the eye-safe spectral region were obtained from passively *Q*-switched microchip lasers that use Yb,Er:glass as the gain medium and $Co^{2+}:MgAl_2O_4$ ($Co^{2+}:MALO$) as the saturable absorber. When pumped with a 1-W 975-nm diode laser, these devices have produced output pulses of ~5-ns duration at repetition rates up to 25 kHz, with peak powers as high as 1.6 kW and average output powers up to 150 mW. At low duty cycles, pulses as short as 880 ps, pulse energies as high as 110 μJ, and peak powers in excess of 35 kW have been demonstrated.

Other combinations of gain medium and bulk solid-state saturable absorber have been used in *Q*-switched microchip lasers operating at a variety of wavelengths. Cr^{4+}:YAG has been used with numerous gain media at wavelengths between 0.91 and 1.08 μm. The Cr^{5+}-vanadates are a relatively new family of saturable absorbers that are used in the same spectral region. Although lasers based on them have not yet demonstrated the short pulse durations or high peak powers that are obtained with Cr^{4+}:YAG, they offer the potential for quasimonolithic and monolithic integration with vanadate gain media. V^{3+}:YAG has been used as a saturable absorber over the spectral range from 0.93 to 1.44 μm. It is most useful in the long-wavelength portion of this range, where Cr^{4+}:YAG is not an option. $Co^{2+}:LaMgAl_{11}O_{19}$ (Co^{2+}:LMA) and Co^{2+}:MALO extend the coverage of solid-state saturable absorbers into the eye-safe spectral region.

Bulk semiconductor saturable absorbers have been used to *Q* switch miniature solid-state lasers at wavelengths from 1 to 2 μm, but have a much lower damage threshold than the solid-state saturable absorbers discussed above and are therefore rarely used. They also have very different thermal and mechanical properties than solid-state gain media, making robust integration of miniature devices challenging.

Q Switching with Semiconductor Saturable-Absorber Mirrors

Semiconductor saturable-absorber mirrors (SESAMs) contain quantum-well saturable absorbers. When high-intensity light at the proper wavelength is incident on the mirror the absorption of the quantum wells saturates and the reflectivity of the mirror increases. In a passively *Q*-switched microchip laser employing a SESAM, the SESAM is used as one of the cavity mirrors.

When SESAMs are used to *Q* switch a microchip laser, the physical length of the saturable-absorber region of the microchip cavity is small and its contribution to the round-trip time of light in the laser cavity is negligible, resulting in the shortest possible *Q*-switched pulses. SESAMs have extremely short upper-state lifetimes, which allow *Q*-switched lasers employing them to operate at very high pulse repetition rates. One of the main limitations of SESAMs is their relatively low damage threshold.

A practical consideration when using SESAMs is that they typically cannot be used as input or output couplers. As a result, the output coupler is usually on the pump-side face of the laser, as shown in Fig. 4. Also, the thermal-expansion coefficients of SESAMs are not well matched to solid-state gain media, making robust bonding of the gain medium to the saturable absorber challenging.

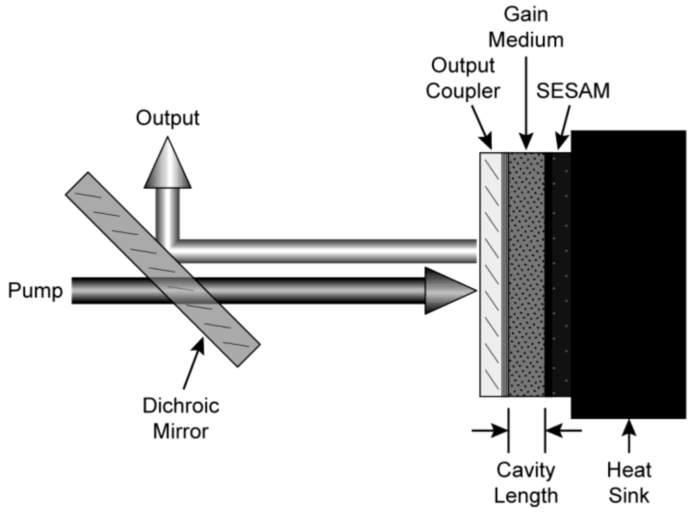


Figure 4.
Typical configuration for a passively *Q*-switched microchip laser employing a SESAM *Q* switch.

As a result of their advantages and limitation, SESAMs are most attractive in applications requiring short, low-energy pulses, and where requirements on the system's robustness can be relaxed. In this regime, they can be operated at very high repetition rates, can produce extremely short pulses, and can be engineered to work with gain media at many different wavelengths.

$Nd:YVO_4$ microchip lasers passively *Q* switched with SESAMs have produced 1.064-µm output pulses as short as 16 ps, and have been pulsed at repetition rates up to 7 MHz. SESAMs have also been used to *Q* switch microchip lasers operating near 1.03 µm, 1.34 µm, and 1.5 µm. The largest pulse energy reported for a passively *Q*-switched microchip laser using a SESAM is 4 µJ, with tens to hundreds of nanojoules being more typical.

Mode Locking

Although many microchip lasers are designed to operate in a single longitudinal mode, they need not be. Optical-domain generation of millimeter-wave signals for fiber radio led to the development of monolithic electro-optically mode-locked 1.085-µm $Nd:LiNbO_3$ microchip lasers with pulse widths as short as 18.6 ps and repetition rates up to 20 GHz. In this application, the repetition rate of the laser is the radio carrier frequency.

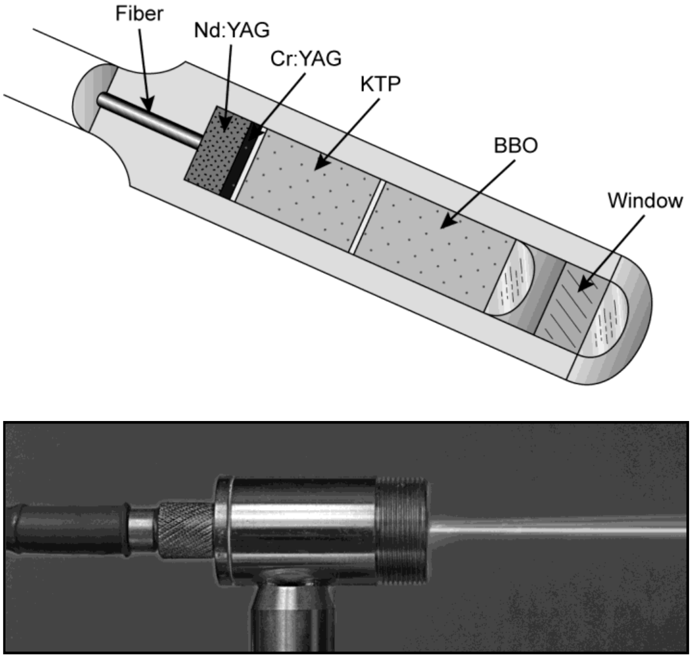


Figure 5.
Fiber-coupled 266-nm frequency-quadrupled passively *Q*-switched microchip laser: (top) schematic and (bottom) photograph of working device mounted on 12.7-mm-dia. post.

Frequency Conversion and Amplification

Nonlinear frequency generation is an important adjunct to microchip laser technology. The high peak powers obtained from *Q*-switched microchip lasers have enabled a variety of miniature nonlinear optical devices. Harmonic generation, frequency mixing, parametric conversion, and stimulated Raman scattering have been used with passively *Q*-switched microchip lasers for frequency conversion to wavelengths covering the entire spectrum from 213 nm to 8.1 µm in extremely compact optical systems.

Many applications for microchip lasers require harmonic conversion of the laser's infrared output. Because of its high peak intensity, the output of even low-average-power Nd:YAG/Cr^{4+}:YAG passively *Q*-switched microchip lasers can be efficiently harmonically converted by placing the appropriate nonlinear crystals near the output facet of the laser with no intervening optics, as shown in Fig. 5. With this approach, a 1-W-pumped 1.064-µm Nd:YAG/Cr^{4+}:YAG passively *Q*-switched microchip laser has been frequency converted to produce 7 µJ of second-harmonic (532-nm green), 1.5 µJ of third-harmonic

(355-nm UV), 1.5 µJ of fourth-harmonic (266-nm UV), and 50 nJ of fifth-harmonic (213-nm UV) light at a typical pulse repetition rate of 10 kHz.

As an alternative to nonlinear frequency generation, the output of passively *Q*-switched microchip lasers and its harmonics have been used as a pump to gain switch miniature lasers in the ultraviolet, visible, and infrared portions of the spectrum. The high peak powers of *Q*-switched microchip lasers have also been exploited in fibers to generate white-light continua, and sub-200-fs pulses through a process that involves self-phase modulation, spectral filtering, and pulse compression.

For many applications the output power, or energy, produced directly by a microchip laser is sufficient. For numerous others, some amplification is required. A wide variety of amplifiers have been used in conjunction with microchip lasers, in systems that take advantage of the waveforms and near-ideal mode properties that they produce.

Applications

Within their range of capabilities, microchip lasers are the simplest, most compact, and most robust implementation of solid-state lasers. CW microchip lasers face strong competition from diode lasers and fiber lasers. Diode lasers are more efficient, smaller, and simpler, and are available at a greater variety of wavelengths. Fiber lasers also tend to be more efficient and can produce higher output powers in a fundamental transverse mode. To compete against either of these technologies, cw microchip lasers need to find a niche application that exploits their unique spectral properties. Nonetheless, the cw microchip geometry has established itself as a testing ground for newly developed gain media.

On the other hand, *Q*-switched microchip lasers provide capabilities that cannot be matched by semiconductor devices or fiber lasers. Semiconductor diode lasers have a very limited capacity to store energy, and their facets are damaged at very modest optical intensities. Fiber lasers have much longer cavities, which prevent them from producing short *Q*-switched pulses and make them susceptible to undesirable nonlinear effects at peak powers well below those demonstrated with *Q*-switched microchip lasers. Fiber amplifiers can be used to increase the peak power from pulsed semiconductor diodes, but this requires several stages of amplification, results in more complicated systems, and is still limited by fiber nonlinearities. Additionally, the amplifier

output has interpulse amplified spontaneous emission that may be detrimental for some applications.

As a result of their small size, robust construction, reliability, and relatively low cost, coupled with their ability to produce energetic, diffraction-limited, Fourier-transform-limited, subnanosecond pulses, passively *Q*-switched microchip lasers have been embraced for applications in high-resolution time-of-flight three-dimensional imaging. Because their high peak output intensity allows for efficient nonlinear generation of ultraviolet light in very compact and reliable formats, they have also been well accepted in the field of ultraviolet fluorescence spectroscopy, and are an integral part of numerous fielded spectroscopic instruments. In addition, passively *Q*-switched microchip lasers have made inroads in laser scribing and marking, laser-induced breakdown spectroscopy, and most recently laser ignition. The continued development of the technology will be driven by applications.

Additional Reading

An expanded, extensively referenced discussion of the material treated in this article is available in:

Zayhowski, J. J. (2013). Microchip lasers. In: Denker, B. and Shklovsky, E. (eds.) *Handbook of solid-state lasers: materials, systems and applications,* Ch. 14. Cambridge, UK: Woodhead Publishing.

A single-source, comprehensive, analytic treatment of miniature solid-state lasers, including microchip lasers, can be found in:

Zayhowski, J. J., Welford, D., and Harrison, J. (2007). Miniature solid-state lasers. In: Gupta, M. C. and Ballato, J. (eds.) *The handbook of photonics.* 2nd ed, Ch. 10. Boca Raton, Florida: CRC Press.